ON THE USE OF ROBOTICS FORMALISM IN THE DESCRIPTION AND MODELING OF ANTENNA RANGE POSITIONERS

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A typical positioner used for positioning an antenna under test on an antenna range has two or three rotation axes arranged in such a manner as to facilitate the taking of data along certain paths through the antenna pattern (pattern cuts). It will usually have one horizontal rotation axis (the elevation axis), a vertical axis (the azimuth axis), and possibly an additional axis (sometimes called the roll axis) which is oriented by the other two. In the most straightforward of measurement sequences, all but one of the axes are fixed and the desired axis is rotated over a prescribed range of angles during which data samples of the received signal are taken. The transmit antenna iuminates the antenna under test from a location in the far zone resulting in a plane wave at the positioner. As measurement sequences become more complex, perhaps requiring simultaneous motion of several axes, two needs arise. First, given the desired angular trajectory, one must determine the necessary axis rotations to achieve it. Second, if phase data is to be properly interpreted, one must obtain, for the particular trajectory used, the transmitting antenna / receiving antenna distance for each data sample. These needs can be conveniently met by means of the existing formalism developed for description and control of the behavior of industrial robots. [See, for example, J. J. Craig, Introduction to Robotics, Addison-Wesley, Reading, MA, 1986]

To properly describe the behavior of a given positioner, one must first identify the parameters of the positioner model. We have done this by performing a set of diagnostic phase measurements which effectively measure the transmitting antenna / receiving antenna distance and optimizing the fit between these data and corresponding data generated by a simulated positioner. The fit is optimized by adjusting the geometrical parameters in the positioner model such as the angles between the various rotation axes. Once this parameter identification has been successfully accomplished, the positioner model can be used to prescribe the necessary axis rotations to achieve a desired trajectory and to determine the transmitter / receiver distance for each data point. In fact, even if the positioner is damaged or improperly constructed so as to render, for example, the angle between two ostensibly orthogonal axes significantly different from ninety degrees, robotics modeling can be used to determine the rotations necessary to compensate for the positioner shortcomings and achieve the desired trajectory. In this paper we describe our experiences with this application of robotics.

JET PROPULSION LABORATORY

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09/16/97

TO: R. Pogorzelski

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National Radio Science Meeting

January 5-9, 1998
The University of Colorado at Boulder

October 31, 1997

Mr. Ronald Pogorzelski
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USA

Dear Colleague:

I am happy to inform you that your paper entitled:

On the Use of Robotics Formalism in the Description and Modeling of Antenna Range Positioners

has been accepted for presentation at the 1998 National Radio Science Meeting. It has been scheduled for Session A3-2 on 1/6/98 at 14:00.

All papers (except those ‘scheduled for Friday, January 9) are scheduled in twenty-minute (or in rare instances thirty- or forty-minute) blocks. You should plan to complete your comments well within that time to allow the audience the opportunity to ask questions immediately following your presentation. .

A copy of the Advance Program for the meeting will be sent in November. It will include all program information as well as registration forms and travel and lodging information. The program will be available on the web at *http://cires. Colorado. edu/urstiprogram* after November 10. If you have questions concerning your presentation, the local organizers, Rod Frehlich or Denise Thorsen, can be reached by e-mail at ursi@cires.colorado. edu.

Thank you for your support of URSI and the 1998 National Radio Science Meeting.

Sincerely,

Technical Program Committee

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The formalism developed over the past few decated for the analytical and **numerical treatment of industrial robots provides a convenient tool for** calibration and programming of antenna range positioners. The existence of this formalism enables the application of standard system identification techniques such as the Levenburg-Marquardt algorithm to derive positioner geometry from range phase measurements. Once the positioner geometry is known, robotics can be used to program any desired trajectory and to implement compensation for geometrical defects in the positioner as well as compensation for range variation in phase measurements.

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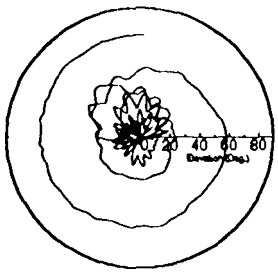
Overview

- Motivated by the "Virtual Spacecraft Concept."
  - Provides for "Antenna in the Loop" link simulation.
  - Antenna on a test range controlled by FST.
  - Requires complex positioner motion.
- Positioner geometry needed to enable the simulation.
  - Diagnostics
  - Compensation

The work described here was motivated by the so-called "Virtual Spacecraft Concept" in which a future spacecraft is simulated initially by computer models of its subsystems. As the subsystems are developed in hardware, breadboard subsystems replace the computer models until ultimately, the simulation is nearly all hardware. In replacing a computer model of an antenna with hardware, we envision the antenna on the measurement range connected to the communications subsystem simulation. In simulating communication during spacecraft maneuvers, the positioner must move the antenna to make the transmit antenna execute the same trajectory in the field ofview of the antenna as would the earth during the actual mission. This can require complex multiaxis motion. Moreover, to program this motion with high accuracy, one must know the positioner geometry with corresponding accuracy. Then in addition to compensating for positioner errors one may also compensate for changes in the distance to the transmit site during the motion so as to obtain true phase measurements representative of the actual earth spacecraft link.

Link Simulation



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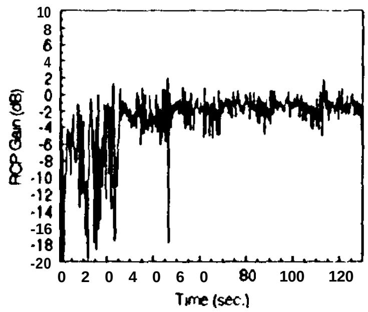
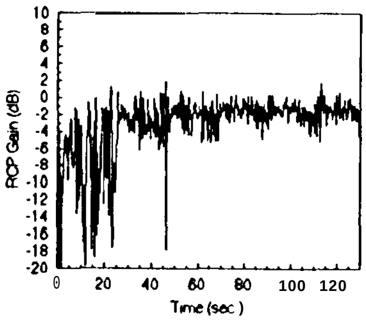


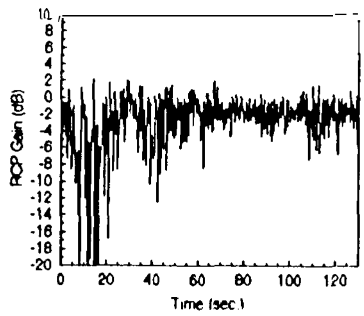
Calculated ● tenna gain during descent.

This **is an** example application which required a very complicated trajectory. This represents the trajectory of the ‘earth in the field of view of the Mars Pathfinder lander low gain antenna during the descent to the surface of Mars. The graph on the right shows the computed right circular polarization signal magnitude variation due to motion along this trajectory.

Link Simulation (Continued)



Calculated antenna **gain during** descent.



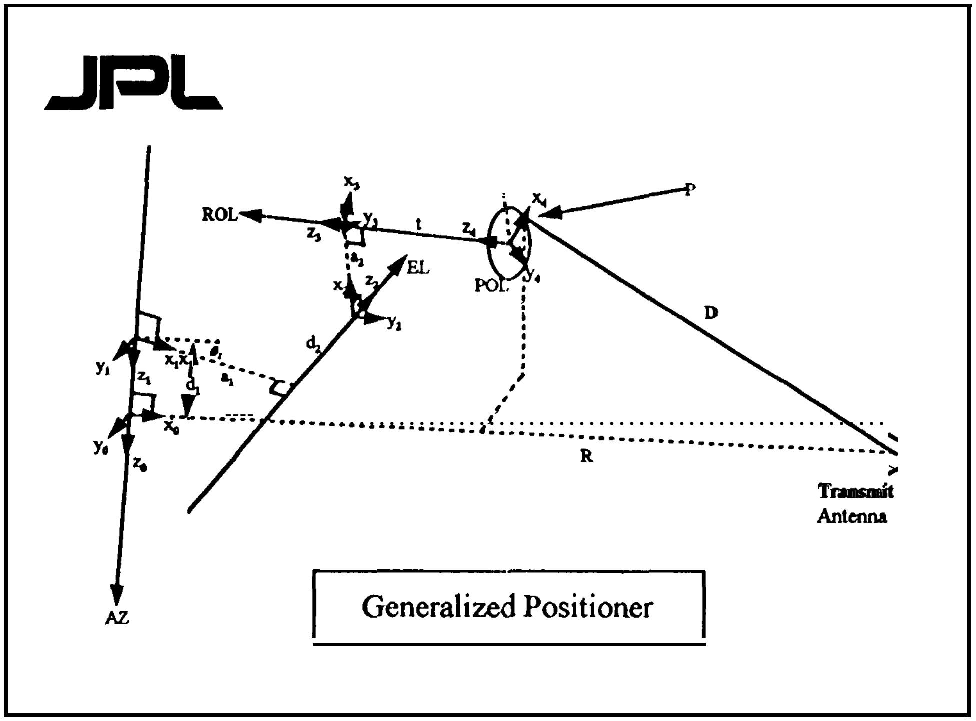
Measured **antenna gain during descent.**

This shows a comparison between the computed gain variation and that measured using a crude mock-up of the lander. Qualitative agreement to the level expected considering the crudeness of the mock-up is evident.

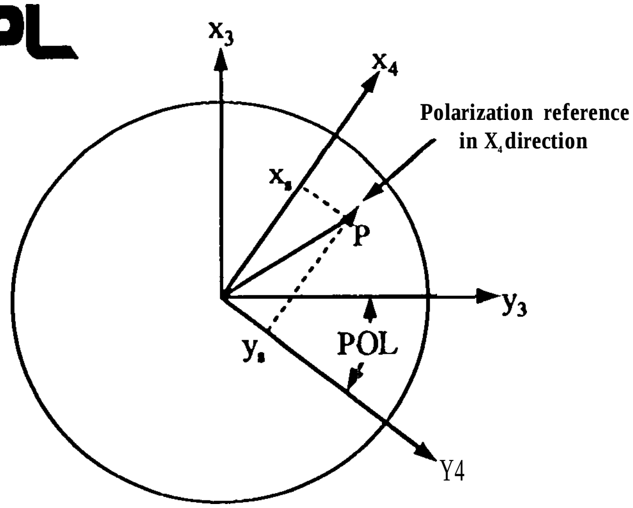
Positioner Geometry

- A positioner is a robot.
  - – Well established theoretical description available.
  - – Standard system identification techniques applicable,
- Robotics provides:
  - – Full description of geometry.
  - – Means of programming arbitrary trajectories.
  - – Means for compensating for defects.

The starting point of the development is that we recognize the positioner to be a robot and we apply the established theoretical description. This will provide a convenient and compact description of the positioner geometry and a convenient formalism in terms of which to describe trajectory programming and error compensation,



A robot is viewed as a series of links connected with hinges. The usual **positioner actuators rotate these hinges. Associated with each hinge is a coordinate system with z axis along the hinge and x axis being the mutual perpendicular between that hinge axis and the next. The geometry is thus completely described by giving the perpendicular distances(a) between the hinge axes, angles (α) between the hinge axes, and the distances along each axis between the intersections with the perpendiculars to the preceding and succeeding hinges (d). In operation, the** hinge **angles (θ) are varied to** produce the desired motion-of the point P. The point P is described by a four vector in coordinate system 4 and a cascade of matrices describing transformation through coordinate systems 3,2,and 1 lead to an overall transformation of the point P into the base coordinate system O.



Polarization Detail

Although our position **has** only three **axes,** we have added a fourth coordinate **system to describe the polarization of the** test antenna. Polarization is assumed to be linear and directed along the x axis of the fourth coordinate system. By properly setting the x and y coordinate of the antenna and the rotation angle, POL, one can achieve any linear polarization and any position desired.

Robotics Model*

$$ {}^{0}P = {}^{0}_{4}T\ {}^{4}P = {}^{0}_{1}T\ {}^{1}_{2}T\ {}^{2}_{3}T\ {}^{3}_{4}T\ {}^{4}P $$

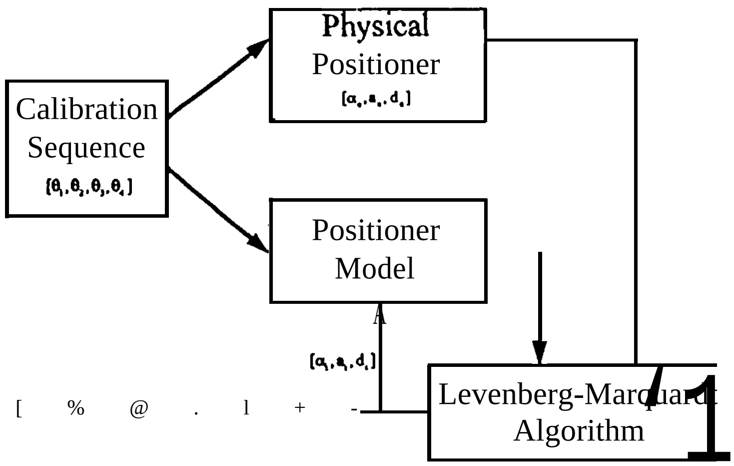
$$ {}^{i-1}_{\ \ i}T = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_{i-1} \\ \sin\theta_i\cos\alpha_{i-1} & \cos\theta_i\cos\alpha_{i-1} & -sins,., & -d,\ \sin\alpha_{i-1} \\ \sin\theta_i\sin\alpha_{i-1} & \cos\theta_i\sin\alpha_{i-1} & \cos\alpha_{i-1} & d,\cos\alpha_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix} 1 $$

$$ 4P = \begin{bmatrix} x_4 \\ y_4 \\ 0 \\ 1 \end{bmatrix} \qquad D = \sqrt{(R - x_0)^2 + y_0^2 + z_0^2} $$

*J. J. Craig, Introduction to Robotics, Mechanics, and Control, Addison-Wesley, 1986.

This is the matrix description of the coordinate transformations. Each transformation matrix depends on the parameters of the given hinge and the rotation angle of that hinge. The product of all the transformation matrices gives a transformation matrix between coordinate systems 4 and O.

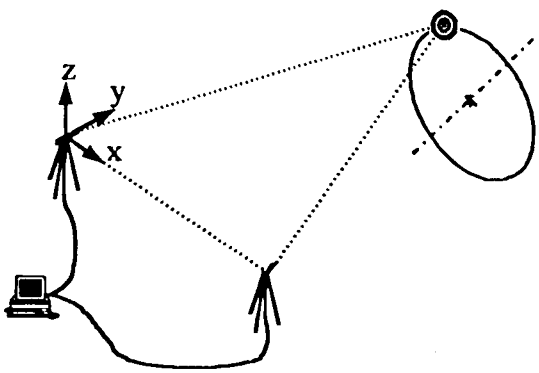
System Identification



In terms of the preceding mathematical description one can develop a computer model of the positioner with variable geometrical parameters. It then becomes necessary to determine these parameters so as to mimic the actual positioner. This is the classical system identification problem. First, we devise a sequence of measurements (pattern cuts if you will) over which we measure the phase variation of the measured signal from, in this case, a circularly polarized transmit antenna. This yields a set of measured data. An important aspect of this is that the transmit antenna must be relatively close to the positioner for the measurement to be effective in identifying the parameters. In our case this measurement was done at 8.45 GHz and the distance was nominally 40 feet.

Having the above described data set in hand, we adjust the parameters of the computer model of the positioner until it produces a best fit to the data. This was accomplished using the standard Levenberg-Marquardt algorithm (Numerical Recipes).

Optical Check



Some aspects of the resulting geometry were checked by using an optical measurement system (Leica's MANCAT System) consisting of two theodolites and a PC. The system establishes a coordinate system as shown and by sight ing on a target from the t wo positions the computer algorithm can be used to provide the Cartesian coordinates of the target. By taking several such measurements and rotating one axis of the position in steps between measurements on obtains a set of points which are then fitted to a circle yielding the radius of the rotation circle, the coordinates of the center, and any desired number of points along the rotation axis. When this is done for all three axes of the positioner, the resulting data can be used to determine the angles and distances between the axes for comparison with the results derived from the phase data.

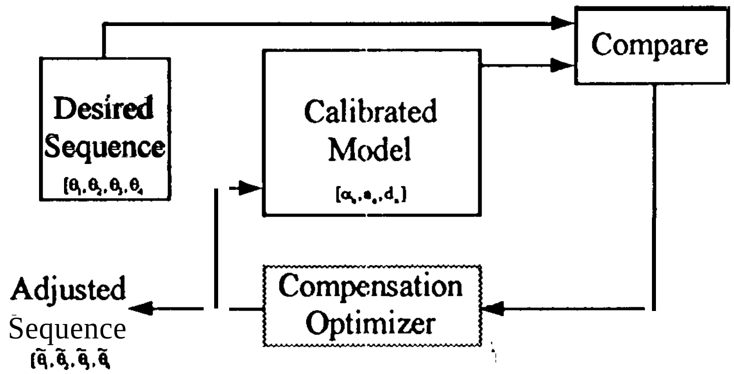
System Identification output

NUMBER OF DATA POINTS:	1086	
ONE SIGMA PHASE ERROR:	20.0000	DEGREES
WAVELENGTH:	1.40000	INCHES
CHISQUARE:	1302.31	
NUMBER O? ITCRATIONS:	16	

PARAMETER	INITIAL	EXPECTED	ESTIMATE	SIGMA	UNITS	FIXED
AZIMUTH OFFSET ANGLE:	0.00000	0.00000	-0.78086	0.02714	DEGREES	
ELEVATION OFFSET ANGLE:	0.00000	0.00000	0.02979	0.01959	DEGREES	
ROLL OFFSET ANGLE:	0.00000	0.00000	-0.31178	0.14100		
POL OFFSET ANGLE:	0.00000	0.00000	0.00000	0.00000	DEGREES	x
AZ AXIS HEIGHT:	230.00000	251.25000	250.09961	0.02074	INCHES	
SHIFT ALONG ELEVATION AXIS:	0.00000	0.66000	0.60284	0.01138	INCHES	
AZ AXIS / EL AXIS ANGLE:	90 .00000	89.72080	89.80862	0.01204	DEGREES	
AZ AXIS / EL AXIS DISTANCE:	10.00000	21.71210	21.46828	0.01630	INCHES	
EL AXIS / ROLL AXIS ANGLE:	*0.00000	89.95320	89.49617	0.02195	DEGREES	
EL AXIS / ROLL AXIS DISTANCE:	0.00000	0.04312	-0.'30393	0.02261	INCHES	
ROLLAXIS EXTZNS1OI4:	12.00000	8.00000	8.07395	0.01177	INCHES	
X ANTENNA POSITION:	-20.00000	-30.75000	-10.011>9	0.01167	INCHES	
Y ANTENNA POSITION:	0.00000	0.00000	0.37934	0.074s1	INCHES	
TRANSMITTER DISTANCE:	461.29999	462.25000	463.29999	0.00000	INCHES	x
OVERALL PHASE OFFSET:	-346.79999	-346.79999	-346.79999	0.00000	WAVELENGTHS	X

This is an example of the output of the Levenberg-Marquardt based system identification algorithm. The expected parameters marked are those obtained from the optical measurements and the others by direct measurement or estimate. X's indicate those parameters held fixed during the optimization. There more subtleties involved in this process than can be discussed here. Suffice it to say that depending on the calibration measurements selected, various pairs of parameters can be dependent in such a manner that to get accurate results one or both of them must be fixed. Otherwise the algorithm may change both of them in a compensating manner and give erroneous results. Fortunately, such situations can be detected via the covariance matrix and thus can be avoided.

Compensation Process



Once the positioner parameters have been "identified", the robotics formalism **can again be used to adjust the programming of the positioner axis controllers to compensate for non-orthogonality of the axes and mis-calibration of the angles while determining the necessary axis rotations to achieve the desired measurement trajectory. Moreover, during the measurement on that trajectory, the distance between the transmit and test antennas** varies introducing artifacts in the phase measurements. This distance variation is now, however, known and can thus be removed leaving only the actual phase variation of the antenna under test.

JPL Concluding Remarks

- Positioners can be calibrated using robotics formalism.
- Robotics provides geometrical description.
- System identification techniques provide calibration,
- Robotics provides:
  - Trajectory programming.
  - Phase correction.
  - Error compensation.

We have shown how robotics formalism can be used to provide a convenient **description of range positioner geometry. We have used this formalism in** performing and processing calibration measurements to determine the geometrical parameters of the positioner and described how these parameters can be used in programming desired measurement trajectories, in phase correction, and in error compensation. As these techniques are refined, routine re-calibration of positioners can become an integral and automated part of antenna measurements. We believe that this is essential if accurate and meaningful phase data is to be taken particularly as the measurement frequency increases. Fortunately, the accuracy of this calibration technique increases with frequency. One might even consider doing the calibration at a higher frequency than that of the intended subsequent measurement to improve the accuracy.